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Evaporation of a bicomponent droplet during depressurization

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ABSTRACT

This paper reports an experimental and numerical study of evaporation process of a two-volatile bicomponent (ethanol/water and acetic acid/water) droplet during depressurization. The environmental pressure, the ambient temperature, and the droplet temperature are investigated during the experiments. A mathematic model is then constructed to simulate the droplet evaporation process. The model solves one-dimensional heat conduction equation and species diffusion equation to acquire the temperature distribution and the concentration distribution inside the droplet. The activity coefficient is introduced to imitate the vapor partial pressure at the droplet surface. By numerical calculations, the variations of temperature distribution and concentration distribution within the ethanol/water droplet and the acetic acid/water droplet are discussed. The effects of composition, final ambient pressure and initial droplet diameter on droplet evaporation are also analyzed in the current study. Results show that the model predictions agree well with the measured temperature data, demonstrating the soundness of the present model and providing insight into the complex heat and mass transfer during the evaporation process of a bicomponent droplet under depressurization.

1. Introduction

Droplet evaporation during depressurization is a coupled heat and mass transfer process accompanied with phase change, which has been widely used in spray drying, flash distillation, and desalination. Many studies have so far investigated water droplet evaporation under reduced pressure. For experimental studies, Owen and Jalil [1] recorded the transient pressure and the droplet temperature during flash evaporation through the droplet hanging method. Satoh et al. [2], Liu et al. [3] and Du et al. [4] experimentally investigated the shape change and the temperature variation of a water droplet during rapid evaporation. While for theoretical studies, Shin et al. [5] and Kim et al. [6] analyzed the heat and mass transfer process of a water droplet during rapid evaporation by using diffusion control model. Zhang et al. [7] established a lumped thermodynamic model to predict the droplet temperature variation during flash evaporation and freezing process. Cheng et al. [8] developed a comprehensive mathematical model of vacuum flash evaporation cooling of a water droplet based on the film controlled evaporation model and numerical analysis of the droplet temperature and diameter after evaporation. Besides, Aguilar et al. [9] and Zhou et al. [10] experimentally investigated the formation and the dynamic characteristics of spray flash evaporation. The mean size and the temperature of spray droplets were experimentally obtained and numerically predicted.

Although rapid evaporation process of a water droplet during depressurization has received considerable attention, few studies have been research on the evaporation process of a bicomponent droplet during depressurization. Luo et al. [11] experimentally investigated the factors influencing the temperature variation of a brine droplet under reduced pressure. Those parameters involve initial salt concentration, final ambient pressure, initial droplet temperature and initial droplet diameter. Zhang et al. [12,13] studied the steam carrying effect in static flash of both pure water and aqueous NaCl solution. Muthunayagam et al. [14] developed a vapor diffusion model to estimate the variations of droplet temperature and diameter during evaporation process of a saline water droplet at low temperatures and reduced pressures. Liu et al. [15] constructed a mathematical model to simulate the evaporation process of a saline droplet during depressurization. The influencing factors on saline droplet temperature were theoretically analyzed. Nešić et al. [16] presented a more detailed description of various stages of droplet evaporation and drying. Their investigation was mainly focused on solid layer formation of a droplet containing colloidal mater. Gopireddy et al. [17] numerically studied the evaporation and drying process of a droplet of polymer in water and mannitol in water. The effects of drying conditions such

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Nomenclature

A_C	cross section area in Eq. (45)
B_M	Spalding mass transfer number
B_T	Spalding heat transfer number
C_P	specific heat capacity (J kg^{-1} K^{-1})
D	diffusion coefficient (m^2 s^{-1})
L	latent heat of vaporization (J kg^{-1})
Le	Lewis number
M	molecular weight (kg mol^{-1})
m	mass (kg)
$\dot{m}$	mass vaporization rate (kg s^{-1})
Nu	Nusselt number
P	pressure (Pa)
Pe	Peclet number
Pr	Prandtl number
q	heat flux (W m^{-2})
R	gas constant(J mol^{-1} K^{-1}))
Re	Reynolds number
r	radial distance (m)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
t	time (s)
u_a	air velocity (m s^{-1})
u_s	maximal liquid velocity at droplet surface (m s^{-1})
V	volume of the test vessel
X	molar fraction
Y	mass fraction

Greek symbols

α	the parameter in Eq. (35)
β	the parameter in Eq. (35)
γ	activity coefficient
ε	the fraction of evaporation rate in Eq. (22); or characteristic Lennard–Jones energies
η	dimensionless factor in computational coordinate
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	characteristic Lennard–Jones lengths
φ	parameter defined by Eqs. (41) and (42)
χ	Effective coefficient

Subscripts

a	ambient air
c	droplet center
eff	effective
h	convection
i	index for species
l	liquid
m	evaporation
r	reference
s	droplet surface
v	vapor phase
0	initial state

Superscripts and overscore

–	average value
*	modified value

as gas velocity, temperature, and relative humidity on evaporation and drying rate were analyzed. In all the previous work, only water evaporates within the droplets.

However, the evaporation process of a two-volatile component (such as: water/ethanol) droplet, also called bicomponent droplet, is more complex. The variation of species concentration during evaporation further increases the complexity of the problem. Sazhin et al. [18,19] experimentally and theoretically studied heating and evaporation process of a bicomponent droplet at atmospheric pressure. The model considered the distribution of temperature and diffusion of liquid species inside the droplet, the effect of recirculation in the moving droplets on heat and mass diffusion, and the effect of the non-unity activity coefficient. The time evolutions of droplet temperature were discussed by comparing numerical results with experimental data. Maqua et al. [20] experimentally measured temperature variation of a bicomponent droplet in hot air plume by applying the three color laser induced fluorescence technique. The influences of initial composition and droplet diameter were revealed. Yarin et al. [21] theoretically and experimentally investigated the evaporation of acoustically levitated droplets of binary liquid mixtures. The temporal evolutions of the droplets surface and the aspect ratio of the droplet contour were explored. Raghuram et al. [22] numerical studied the evaporation of stationary, spherical, two-component liquid droplets exposed to forced convective hot air at atmosphere pressure. The relative strengths of forced convection and Marangoni convection, the resultant flow, temperature and species fields within the droplet were mainly analyzed. Ebrahimian et al. [23] developed a predictive evaporation model for multi-component hydrocarbon droplets at atmospheric and high pressures to investigate effects of pressure and composition.

Up to now, the investigations on evaporation of a bicomponent droplet have covered the high pressure domain as well as the atmospheric environment, which can be applied to the combustion of liquid fuel. However, the evaporation characteristics of a bicomponent droplet during depressurization remain unknown. Also, the temperature and concentration distributions inside the droplet have not been investigated in detail. The present paper aims to explore evaporation process of a bicomponent droplet during depressurization, with the two components evaporating simultaneously. An experimental work has been performed to measure the environmental pressure, the ambient temperature and the droplet temperature during depressurization. A mathematical model is developed to simulate the droplet temperature variation with the gradual decrease in ambient pressure. The proposed model also simulates the heat and mass transfers because of evaporation and convection at the droplet surface, accompanying the species diffusion and the temperature gradient inside the droplet. The activity coefficient is introduced to simulate the vapor partial pressure at the droplet surface. The effects of droplet components and final environmental pressure on droplet evaporation are theoretically analyzed for ethanol/water droplets and acetic acid/water droplets. The model calculations help to comprehensively understand the heat and mass transfer process of evaporation of a bicomponent droplet during depressurization.

2. Experimental System

The schematic drawing of the experimental apparatus is shown in Fig. 1. It consists of four subsystems including a test vessel, a vacuum system, a photography system and a data acquisition sys-